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ASTRONOMY AND ASTROPHYSICS

Gamma-Ray Bursts and the Origin of Chondrules and Planets

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Abstract. The effect of a nearby γ-ray burst (GRB) on the preplanetary solar nebula is considered. The intense irradiation by x-rays and γ-rays would have caused dust balls to become molten in a matter of seconds, cooling more slowly to form chondrules. The role of iron is crucial in this process because it was the major absorber of x-rays between 7 keV and 30 keV. In this scenario, chondrules formed at the same time across the side of the nebula toward the GRB source. At least 27 Earth masses (M⊕) could have been produced in the nebula with well mixed gas and dust of solar composition, increasing to 100 M⊕ with only moderate depletion of nebular gases. The chondrules combined to form meteorites and possibly the terrestrial planets, the cores of the giant planets and chondrules in comets. Assuming GRBs are linked to massive stars like supernovae, the probability of a GRB within 100 pc which could form chondrules is about 10^{-3} and the same small probability may apply to other planetary systems being akin to our solar system. A GRB in a nearby galaxy will reveal protoplanetary disks by delayed transient infrared emission from the chondrule formation process. We suggest that a GRB was first detected about 4.5 Gyrs ago and its signature was written in stone and preserved by the chondrules in meteorites.

1. Introduction

Chondrules are millimetre sized, spherical to irregular shaped objects that constitute the major component of most chondrite meteorites that originate in the region between Mars and Jupiter and which fall to the Earth. They appear to have crystallised rapidly from molten or partially molten drops and were described (Sorby, 1877) as "molten drops in a fiery rain". The properties of the chondrules and chondrites have been exquisitely deduced from an extensive series of experiments and two conferences have been devoted completely to chondrules (King, 1983; Hewins et al., 1996). The mineralogy of chondrules is dominated by olivine ($(FeMg)_2SiO_4$) and pyroxene ($(FeMg)SiO_3$) and there is a wide range of compositions for all elements. This diversity is consistent with the melting of heterogeneous precursor solids or dust balls. The age of chondrules indicate they formed very early in the solar system. The calcium-, aluminium-rich inclusions (CAIs) are refractory inclusions in carbonaceous and ordinary chondrites that predate the chondrules by several million years and are the oldest known solid materials produced in the nebula (Swindle et al., 1996). The first 10^7 years in the complicated development of the solar system has been comprehensively covered in an attempt to understand the CAI to chondrule time interval of several million years (Cameron, 1995).

The presence of volatile elements in the chondrules indicate that the high temperature melting period lasted for a matter of seconds to minutes. Experiments based on chemical and textural compositions of chondrules suggest cooling rates that were much slower than radiative cooling of isolated chondrules and imply they were made in some large quantity in relatively opaque nebular domains (Yu & Hewins, 1998). Volatile elements such as alkalis and sulphur occur in chondrule interiors as primary constituents and indicate that some chondrule precursor materials must have reacted with cool nebula gases at ambient temperatures less than 650 K.

The heat source that melted the chondrules remains uncertain and a critical summary of the heating mechanisms was given by Boss (1996). These methods include giant lightning flashes (Horanyi et al., 1995) and shock wave heating of the precursor materials (Wood, 1988). All heat sources proposed to form the chondrules are local to the solar nebula. We propose that the chondrules were flash heated to melting point by a nearby GRB when the precursor materials efficiently absorbed x-rays and low energy γ-rays. The distance to the source was about 300 light years (or 100 pc) for a GRB output of 10^{53} ergs and was estimated using the minimum value of 2×10^{10} erg g^{-1} required to heat and melt the precursor grains (Grossman et al., 1988; Wasson, 1993). The role of nearby supernovae that preceded the formation of the solar system have been considered (Cameron et al., 1995) along with the serious consequences for life on Earth of nearby supernovae (Ruderman, 1974; Clark et al., 1977) and GRBs (Thorsett,

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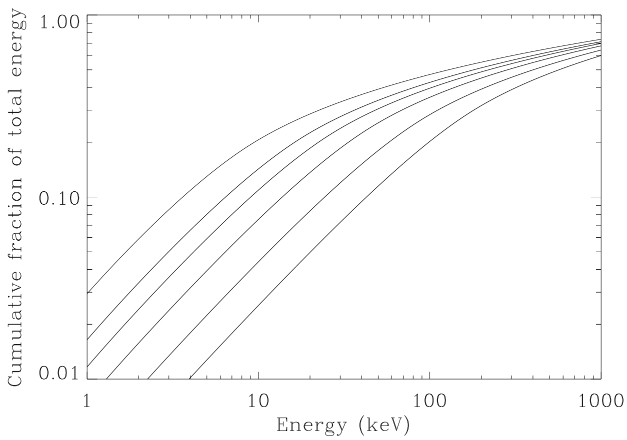

Fig. 1. The cumulative fraction of GRB energy as a function of photon energy for assumed spectral parameters α = -1, β = -2, E_o = 5, 10, 15, 25, 50 and 100 keV and redshift of 0.8.

1995). The consequences of a nearby GRB on the early solar nebula have not been considered elsewhere.

The properties of GRBs relevent to chondrule formation are presented in section 2. The absorption of x-rays and γ-rays by gas and dust in the solar nebula is considered in section 3. The effects of sudden chondrule production on the formation of the planets are presented in section 4. The probability of a GRB producing chondrules is considered in section 5.

2. γ-Ray Bursts (GRBs) as a Heat Source

Since their discovery thirty years ago the properties of GRBs have been determined by an outstanding series of experiments that were deployed on more than twenty spacecraft at distances up to several astronomical units (AU) from the Earth and during one period 11 spacecraft were used to study the same GRBs. The properties of GRBs have recently been reviewed (Fishman & Meegan, 1995; Piran, 1999) and are now the subject of intense research. GRBs are extragalactic in origin and release collossal amounts of energy, 10^{52} to 4×10^{54} ergs assuming isotropic emission, for the GRBs with known redshift. The BeppoSAX satellite discovered x-ray afterglow that decayed with time t in the range $t^{-1.1}$ to $t^{-1.5}$ (Costa et al., 1997; Piro et al., 1998; Nicastro et al., 1998). Simultaneous optical emission was detected from the spectacular GRB 990123 at the level of about 10^{-5} of the energy in γ-rays (Akerlof et al., 1999), but this emission is too weak to influence chondrule formation.

The progenitors of GRBs are not known but merging neutron stars have been suggested. One GRB is known to have occurred in a luminous infrared galaxy (Hanlon et al., 1999), and some GRBs are close to star forming regions suggesting a connection with massive stars (Bloom et al., 1998). Models of 'failed supernova' and 'hypernova' have been proposed (Woosley, 1993; Paczynski, 1998) in which the inner core of a massive rotating star collapses to a black hole while the outer core forms a massive disk or torus that somehow generates a relativistic fireball and GRB. In these models GRBs represent the violent end to massive stars.

GRBs have a lognormal bimodal distribution of durations that peak at about 0.3 s and 30 s respectively. The wide range of pulse shapes with complex time profiles have been described using lognormal distributions and GRBs have been called cosmic lightning because of their statistical similiarities with terrestrial lightning (McBreen et al., 1994; Hurley et al., 1998; Stern & Svensson, 1996). The photon spectra are well described by a power-law with a low energy slope α, a break energy E_o and a high energy power law with slope β. The functional form, for low energies, is given by (Band et al., 1993) :

$$N(E) = AE^{\alpha}e^{-E/E_o} \text{ and } N(E) = BE^{\beta}, \quad \alpha > \beta$$

The value of E_o ranges from 2 keV to over 1 MeV and the indices α and β are typically -1 and -2 respectively. There is an excess of $\approx$ 10 keV x-rays above this functional form in about 15% of GRBs (Preece et al., 1996).

The spectral energy distributions of a sample of GRBs have been extrapolated and integrated from 0.1 keV to 10 MeV using a sample of values for E_o compatible with BATSE (Band et al., 1993) and Ginga results (Strohmayer et al., 1998). The cumulative fraction of the total energy in GRBs is given in Figure 1 where a redshift correction of z = 0.8 has been applied to all the spectra. There is sufficient energy to melt solar nebula grains provided absorption of the x-rays and γ-rays is reasonably efficient.

3. Attenuation of X-Rays and γ-Rays

The absorption of the GRB energy by the gas and dust in the nebula would have occurred through the processes of photoelectric absorption and Compton scattering. The combined cross-sections due to these processes for the elements from H to Fe are plotted in Figure 2. Solar abundance values were adopted for the nebula (Anders & Grevesse, 1989) and the photoelectric and Compton cross-sections for the elements have been used (Veigele, 1973) with the exception of molecular hydrogen (H_2) where a value of 1.25 times the elemental photoelectric cross-section was adopted (Morrison & McCammon, 1983). The photoelectric effect absorbs the photon completely but in Compton scattering only a fraction of the energy is removed per scattering and this fraction varies from 0.14 at 100 keV to 0.45 at 1 MeV. The product of the Compton cross-section by the fraction of the energy absorbed in the first scattering was used for the Compton cross-section and many scatterings may occur before the degraded photon is finally absorbed by the photoelectric effect. Decreasing the abundance of H and He by a factor of 10 relative

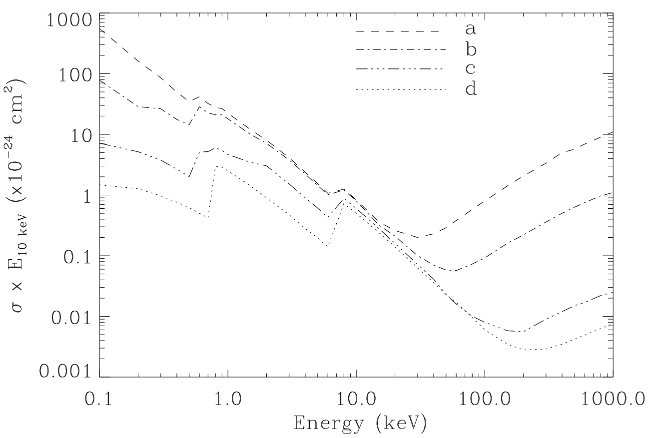

Fig. 2. The combined photoelectric and Compton cross sections relative to H as a function of energy, scaled by E/10 keV for clarity of presentation. (a) The elements H to Fe that are at least as abundant as Fe (H, He, C, N, O, Ne, Mg, Si, Fe) (b) the same elements as in (a) with solar abundance of H and He reduced by 10 (c) The precursor dust combination $Fe_{0.9}SiMg_{1.1}O_4$ and (d) the element Fe.

to the solar value significantly reduces the cross-section below 1 keV and above 20 keV (Figure 2b). The cross-section of Fe (Figure 2d) is dominant between the K edge at 7.1 keV and 30 keV but the upper bound of 30 keV extends to above 50 keV for low abundance of H and He. Fe makes the major contribution to the absorption by the dust and is the key to chondrule formation.

The elements O, Si, Mg and Fe dominate the composition of the chondrules but the composition of the precursor grains has been the subject of much study and speculation (Hewins, 1997). A number of chondrule classification systems have been adopted and early approaches depended mainly on either bulk composition or texture or both. McSween (1977) recognised two main types, type I or FeO poor and type II or FeO rich. However in comparison with chondrules, the fine-ground matrix in chondritic meteorites is more FeO rich than even type II chondrules and it has been proposed that this matrix may be close to the composition of the chondrule precursor (Huang et al., 1996). In this scenario, the precursors of type I chondrules were enriched in Fe and more efficiently heated by x-ray and γ-ray absorption, resulting in the loss of Fe and other volatile elements that ended in the enriched matrix. Type II chondrules appear not to have lost significant amounts of volatiles in the melting process. The composition of the precursor grains may be resolved by new x-ray and γ-ray heating experiments. A composition consisting of solar abundance of oxides of Fe, Si and Mg or $Fe_{0.9}SiMg_{1.1}O_4$ was assumed for the precursor grains and the product of the cross section of this combination by abundance relative to H is plotted in Figure 2c. The x-ray and γ-ray absorption efficiencies of different thicknesses of precursor grains, assuming a density of one, are given in Figure 3 and grains in the range 10 μm to 1 cm are very efficient absorbers in the region where dust dominates the absorption (Figure 2). This range agrees quite well with the measured Weibull and lognormal distributions of chondrule sizes (Martin & Hughes, 1980; Rubin & Keil, 1984). The deficiency of small grains is caused by low absorption efficiency and substantial radiation losses from grains with large surface to volume ratios.

The thickness of the dust layer converted to chondrules depends on the GRB spectrum which must have significant emission below 30 keV where dust absorption dominates (Figure 2) and also on the mixture and distribution of gas and dust in the nebula. For a GRB with 10^{53} ergs and an assumed spectrum α = -1, β = - 2 and E_o = 15 keV (Figure 1), the fraction of GRB energy photoelectrically absorbed by the dust is 20%, increasing to 27% for a factor 10 reduction in H and He. In the simplified case of solar abundance and a uniform mix of gas and dust, the thickness of the chondrule layer created is 0.18 g cm^{-2} corresponding to one optical depth for 30 keV x-rays. The layer thickness increases to about 0.8 g cm^{-2} and 2.0 g cm^{-2} for optical depths to 40 keV and 55 keV x-rays with H and He abundances reduced by factors of 3 and 10 respectively. The thickness of the chondrule layer is therefore controlled by the degree of gas depletion from the nebula. The minimum GRB fluence required to produce chondrule layers of 0.18, 0.8 and 2.0 g cm^{-2} is 1.8×10^{10}, 7.0×10^{10} and 1.5×10^{11} ergs cm^{-2}, adopting 20%, 23% and 27% absorption by the chondrule precursors and 2×10^{10} erg g^{-1} for heating and melting. A fluence of 10^{11} erg cm^{-2} implies a distance of about 100 pc to the source for an output of 10^{53} ergs radiated isotropically. The GRB would also form a layer of chondrules over a large area (10^3 - 10^4 pc^2) in a nearby molecular cloud provided large precursor grains had already formed (Weidenschilling & Ruzmaikina, 1994). The process of chondrule amalgamation might be sufficient to trigger star formation over this region. In this case chondrule formation precedes cloud collapse and star formation. The existence of pre-solar grains in meteorites is well established (Zinner, 1996) but there is no evidence for pre-solar chondrules.

The chondrules cooled at a much slower rate than if they were isolated (Hewins, 1997). They may have been warmed by a fading source or by forming a thermal blanket or a combination of both effects. BeppoSAX discovered x-ray afterglow from GRB sources and the limited measurements show considerable variability between the various GRBs (Costa et al., 1997; Piro et al., 1998). The afterglow typically decreases by at least a factor of 20 in 10^3 s which yields more than a factor of two drop in temperature. This decrease of 3800 K hr^{-1} is too rapid to account for the chemical and textural properties of chondrules (Yu & Hewins, 1998). The chondrules on the far side of the layer from the GRB source cool even more rapidly because of shielding by foreground chondrules and spec-

tral softening of the afterglow. The optical depth of the chondrules to their infrared radiation at a peak of about 1.5 μm is about 0.25 g cm^{-2} assuming all the chondrules have size 0.1 cm (Hood & Horanyi, 1991; Wood, 1988). The x-ray and infrared optical depths are comparable and the cooling rate was further reduced by this thermal blanket.

There are several indicators that the dust was concentrated and/or gas depleted in the nebula when chondrules formed. These include: (1) the increased rate of collisions between plastic and molten chondrules to form adhering pairs (Wasson, 1993), (2) the seeding of melted chondrules with dust grains (Connolly & Hewins, 1995), (3) the O/H ratio well above the solar value (Fegley & Palme, 1985), and (4) the improved absorption efficiency of x-rays and γ-rays by the precursor dust balls. The rims on chondrules indicate time spent in dusty regions.

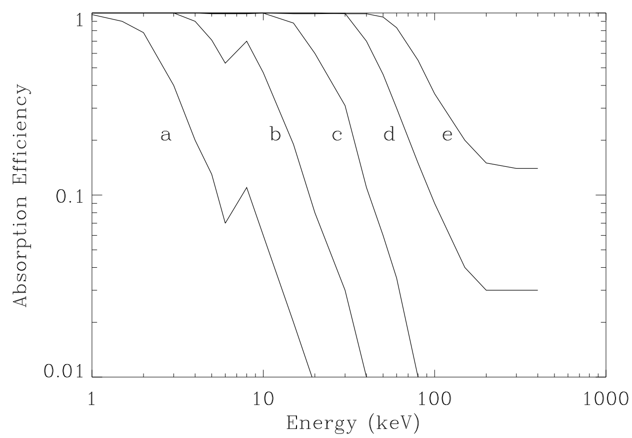

Fig. 3. The absorption efficiency of different thickness of $Fe_{0.9}SiMg_{1.1}O_4$ as a function of energy: (a) 10 μm, (b) 100 μm, (c) 1000 μm, and (d) 1 cm, (e) 5 cm.

4. The Solar Nebula and Chondrules

The formation of the Sun and planets has been the subject of extensive study and is now particularly important because of the recent detections of Jupiter like planets around solar type stars that are inferred to be giant planets (Mayor & Queloz, 1995; Beckwith & Sargent, 1996; Levison et al., 1998). The main model for planetary formation in the solar system is that planets are the end result of a bottom-up assembly process beginning with the accumulation of interstellar grains into millimeter and centimeter sized objects that form in the disk and eventually settle to the midplane where they are brought together to form kilometer sized objects (Mizuno, 1980; Black, 1995). These so called planetesimals proceed through a runaway accretion process to form bodies of lunar size that are eventually accumulated to form the terrestrial planets. In the case of the giant and icy outer planets the process is different (Pollack et al., 1996). A planetary core accretes until a critical mass of about 10 M$\oplus$ is reached. At this point the growing core is unable to sustain an equilibrium atmosphere and a very rapid accretion of nebular gas occurs that gives a giant planet. The total mass of the nebula between 0.35 AU and 36 AU is 0.01 M$\odot$ and is considered the minimum necessary to form the present planets. There are perceived difficulties with this model with regard to timescales because the predominantly H and He composition of Jupiter and Saturn predates the dispersal of the solar nebula (Cameron, 1978).

A number of models have been proposed for distribution of surface densities of dust materials and gases in a preplanetary solar nebula, which is in thermal and gravitational equilibrium. According to Cameron (1995) the nebula surface density as a function of radial distance from the Sun was $\Sigma = \Sigma_0 \, r^{-1.0}$ g cm^{-2} with a normalising value of $\Sigma_0 = 4.25 \times 10^3$ at r = 1 AU. The abundance by mass of rocky and metallic materials was 0.0043 and 0.0137 for icy materials (H_2O, CH_4 and NH_3), that occur beyond about 3 AU.

There are many complicated processes that occur in the evolution of the solar nebula from essentially interstellar grains to planetesimals and planets (e.g. (Cameron, 1995)). Particle radii vary over 11 orders of magnitude from micron sized interstellar particles to planetesimals. It seems likely that planetesimal formation involved at least an early stage of collisional sticking and coagulation of particles. This process depended on poorly constrained properties of the nebula such as turbulence and of the particles themselves such as stickiness and composition. The process of particle accumulation and coagulation is strongly influenced by turbulence which keeps the particles in constant random motion with respect to the gas and many simulations on particle coagulation have been carried out for silicate and icy grains (Cameron, 1995; Weidenschilling, 1980; Weidenschilling & Cuzzi, 1993). In the GRB-chondrule scenario, the chondrules reflect the size distribution of the precursor grains. It is interesting that they have an approximate lognormal distribution. This distribution is generated by particle grinding and collisions and imply these conditions prevailed in the nebula at the time of the GRB (Aitchison & Brown, 1957). Historically the lognormal distribution was developed to account for the size distribution of grains of sand. Turbulence is known to produce structure on many scales and hence the particle distribution in the nebula was probably quite clumpy. To make progress we assume the particles and gas were well mixed and of solar composition. The GRB should have produced a layer of 0.18 g cm^{-2} of chondrules or 27 M$\oplus$ out to r = 36 AU and 100 M$\oplus$ if H and He were depleted uniformly by a factor of 3. In the latter case, three percent and ten percent of the dust is converted to chondrules at r = 1 AU and r = 10 AU respectively. The gas may not have been depleted uniformly across the neb-

ula at the time of the GRB. The compositions of Jupiter and Saturn reveal that they formed before the nebula was depleted of H and He by more than about a factor of 5. The terrestrial planets and giant icy outer planets, Uranus and Neptune, completed their formation after gas depletion from the nebula.

The gas depletion from the inner nebula probably occurred over about 10^7 years by strong solar winds during the FU Orionis and T-Tauri phase of the Sun and from the outer nebula beyond about 9 AU by photo evaporation (Shu et al., 1993). In this scenario the chondrules formed almost simultaneously across the side of the nebula towards the GRB and impacted on the early history of aggregates in the nebula. The chondrules were combined and compacted to form meteorites and this same process should have operated throughout the nebula and led to the formation of the terrestrial planets and possibly the cores of the giant planets. The minimum of 27 $M_\oplus$ is close to the amount estimated (30-40 $M_\oplus$) to form the cores of the four giant planets assuming that chondrules constituted most of the mass. However for chondrules to form the terrestrial planets, then a layer of at least 2 g cm^{-2} was produced out to a few AU, implying significant gas dispersal from the inner nebula by about a factor of 10 at the time of the GRB. The composition of the Earth is not inconsistent with a complete chondrule origin because the inner solar system experienced higher ambient temperatures than the asteroid belt and would have been more efficiently cleaned of gas containing volatile bearing dust (Hewins & Hertzberg, 1996).

There is a major change in the aerodynamic properties on melting of the fluffy precursor material to form chondrules with stopping times increasing by a factor of about 100. However, there seems to be little tendency for them to settle to the midplane because vertical settling requires very low intensities of turbulence (Weidenschilling, 1980; Völk & Morfill, 1991; Cameron, 1995). Somehow the chondrules were size sorted, probably by an aerodynamic process, and concentrated by a large factor to form planetesimals and meteorites of size of order 100 km. A turbulent concentration of particles has been shown to be size-selective and effective for particles with the chondrule size distribution (Cuzzi et al., 1996) where a uniform volume distribution of particles tend to vacate the eddies and concentrate in stagnant zones with concentration factors of order 10^6. The subsequent evolution of the dense concentrations has not been modelled in detail but it is probable that they descended to the midplane and commenced and continued the accretion process of forming planetesimals that include the meteorite parent bodies. Subsequent collisions must merge the planetesimals of size about 100 km to form the terrestrial planets and cores of giant planets. The formation of the cores of the giant planets could have proceeded at a much faster rate than the terrestrial planets because the gas was cooler, less dense and less turbulent and also the chondrules were probably coated with ice and mixed with ice particles that should have significantly improved the sticking co-efficients (Cameron, 1995). These effects should have speeded up the formation of planetesimals in the outer nebula.

The composition of comets is approximately solar and the GRB should have formed chondrules in the region where comets formed. The favoured region is near the Uranus-Neptune zone where perturbations by the protoneptunian group could move the young comets out to the Oort cloud (Whipple, 1989; Mumma et al., 1993). Other models advocate cometary formation further out in the solar system. There are only two ways in which comets can avoid having chondrules: (1) they formed before the GRB, or (2) there were no iron rich dust balls sufficiently large to be melted to form chondrules. The presence or absence of chondrules in comets will yield valuable clues to the cometary and chondrule formation processes. The high precision results that will come from outstanding and ambitious rendezvous and sample return missions will greatly improve our understanding of conditions in the comet forming regions of the solar system.

5. Probability of a nearby GRB

The frequency of nearby supernovae, and hence GRBs assuming they are linked to massive star formation like supernovae, depend on where the solar system was located within the galaxy when it formed. The highest rate of type II supernovae occurs in the two principal spiral arms of the galaxy. The molecular cloud was compressed entering the spiral arm to a condition for star formation and this interaction resulted in a new star cluster that traversed the spiral arm. Massive stars in the cluster evolve rapidly over 10^7 years terminating in type II supernovae. The width of this supernova zone is about 1 kpc because the stars move at about 100 km s^{-1} for 10^7 years (Clark et al., 1977). It is likely that a nearby supernova caused the collapse of the presolar cloud and also seeded the nebula with the radioactive ^{26}Al needed to explain the ^{26}Mg in CAIs (Cameron et al., 1995). The number of supernovae along the spiral arm, within the 1 kpc zone and over a period of 10^7 years, has been estimated at 250 supernovae per 100 pc (Clark et al., 1977).

BATSE observes on average about one GRB per day. This corresponds to one burst per million years per galaxy assuming that the rate of GRBs does not change with cosmological time (Fishman & Meegan, 1995). The average rate changes if allowance is made for beaming or a cosmic evolution of the rate of GRBs. The observations that GRB host galaxies are star forming systems (Hogg & Fruchter, 1998; Fruchter et al., 1999; Bloom et al., 1998) indicates that the rate of GRBs may follow the star formation rate (Wijers et al., 1998; Totani, 1999). In this case GRBs are further away and occur at a lower rate and have significantly greater energy output. At present there is no agreement on the nature of the progenitors of the GRB

explosion although neutron star mergers are a promising candidate (Eichler et al., 1989; Piran, 1999). The list also include failed supernovae (Woosley, 1993), white dwarf collapse (Usov, 1992) and hypernovae (Paczynski, 1998). All these models are consistent with the possibility that GRBs are associated with star forming regions. The lifetime of massive stars is quite short and that of a neutron star binary could be sufficiently short to be close to a star forming region.

There is considerable uncertainty in the cosmological rate of GRBs (Cen, 1998; Krumholz et al., 1998; Che et al., 1999) and a rate of one GRB per galaxy per 10^7 years is adopted which is about 10^5 times less than the supernova rate (Paczynski, 1998). It is also assumed that GRBs are linked to massive stars and the explosion occurs in the supernova zone of the spiral arm. There is a probability of about 0.001 of a GRB occuring within $\pm$ 100 pc of the solar nebula assuming the length of the spiral arms is about 40 kpc and the thickness of the spiral arm perpendicular to the plane is less than 100 pc. The probability will be smaller by many orders of magnitude if GRB explosions occur at random locations throughout the galaxy. There is evidence such as paired and rimmed chondrules that some of them were melted on more than one occasion (Hewins, 1997; Wasson, 1993). The probability of two GRBs impacting on the solar nebula with sufficient energy to melt chondrules is 10^{-6}. The heat source that led to CAI formation is uncertain but it was much more intense and lasted for a longer period than chondrules because most of the refractory dust was evaporated in the process (Wood, 1988). A GRB could have been the heat source but it is very improbable because it must have been within 10 pc to provide the required energy.

If this GRB-chondrule scenario is correct, then only about one planetary system in 1000 should have evolved like the solar system and should preserve evidence for chondrule formation. The solar nebula existed as a detector of intense flashes of radiation for millions of years but recent satellite observations cover less than forty years and have discovered the GRBs and soft γ-ray repeaters (SGRs). There could be other rare transient sources yet to be discovered that influenced the formation of chondrules. In this context the role of the SGRs might have been important (Kouveliotou et al., 1993). There are four known SGRs that are associated with supernova remnants and which have high velocities relative to the nebula. Two of the SGRs have generated intense transients, 5×10^{44} ergs and 2×10^{43} ergs, but these transients are too feeble by about a factor of 10^6 to influence chondrule formation (Hurley et al., 1999). However the number of SGR sources within the galaxy is very uncertain (Hurley et al., 1994; McBreen et al., 1998; Heyl & Kulkarni, 1998) and SGRs may generate much more powerful outbursts shortly after their formation. The recent detection (Galama et al., 1998) of a weak GRB, about 10^{48} ergs, from a type Ib/c supernova suggests that different mechanisms may give rise to a new class of dim supernova-related GRBs.

A GRB in a nearby galaxy (< 100 Mpc) could be used to reveal protoplanetary disks because of the transient infrared emission from chondrule formation. In K band, the transient source would be at the μJy level and good angular resolution is required to separate the transient emission from the galactic background. The transient sources could occur over a period of hundreds of years after the GRB, assuming isotropic GRB emission.

6. Conclusions

It has been shown that a nearby GRB could have melted pre-existing dust balls in the pre-planetary solar nebula and produced chondrules across the nebula at the same time. The probability of a GRB occurring within $\approx$100 pc is about 10^{-3}. Sufficient chondrules could have been produced by this mechanism to account for the meteorites and cores of the giant planets and enough chondrules to completely account for the Earth and the inner planets provided the gas in the inner solar system was depleted by a factor 10. The probability of other planetary systems being similar to the solar system is about 10^{-3}. A GRB in a nearby galaxy could be used to find protoplanetary disks by detecting the transient emission from chondrule formation. Chondrule layers could also be formed in molecular clouds that are near a GRB and have large precursor grains.

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